EXPERIMENTAL GENERATION OF LAMB WAVE DISPERSION USING FOURIER ANALYSIS OF LEAKY MODES

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INTRODUCTION

Conventionally, either swept frequency technique or a combination of swept frequency and geometric analysis is used to produce the experimental Lamb wave dispersion data. This paper proposes a novel method for constructing dispersion curves in solid plates using Fourier analysis of received leaky Lamb wave signals. The Lamb waves are produced by pulsed ultrasound generated using two broad band transducers positioned in a pitch-catch orientation. The relative distances among the plate and the two transducers are set to specific values as per geometric calculations based on beam diffraction. The transducer defocus is used in conjunction with geometric calculation to determine the phase velocity of the Lamb wave mode being monitored. Subsequent to appropriate positioning of the transducers, the plate wave signals are Fourier transformed to obtain a magnitude versus frequency spectrum. Peaks in the spectrum indicate the presence of a Lamb wave root. The feasibility of this method has been tested by successfully constructing a dispersion curve for a steel plate.

CONVENTIONAL SWEPT FREQUENCY TECHNIQUE OF LEAKY LAMB WAVE GENERATION

Leaky Lamb waves are generated by ultrasonic waves that are obliquely incident on an immersed plate at frequencies that excite plate wave modes. The generation of the leaky Lamb waves leads to distortion of the reflected beam in the specular reflection region. A phase cancellation occurs when the leaky Lamb wave and the geometrically (specularly) reflected beam interfere generating a null zone. The null zone is monitored in a swept frequency mode to generate dispersion curves in the traditional method. The sensitivity of the leaky Lamb waves to variations in elastic properties, thickness, and boundary conditions provides valuable information about the material. Theoretical studies by Kundu and Blodgett [1], Yang and Kundu [2,3] and Yang [4] have shown that different Lamb wave modes produce different levels of excitation in various layers in a multilayered solid plate.

The conventional tone burst frequency swept technique is commonly used to experimentally generate Lamb wave roots. Previous efforts of using leaky waves to inspect defects in composite and metal plates include the works of Chimenti and Nayfeh [5], Nagy et al. [6], Pearson and Murri [7], Rose et al. [8], Nayfeh [9], Bar-Cohen and Chimenti [10], Chimenti and Bar-Cohen [11], Martin and Chimenti [12], Mal and Bar-Cohen [13], and Chimenti and Martin [14], Bar-Cohen and Chimenti [15], Chimenti and Fiedler [16], Ditri and Rose [17], Ditri and Rajana [18], Rajana, et al. [19], among others. In this technique, two broad band transducers are positioned in the pitch-catch orientation. The transmitter is excited by a signal function generator, which produces continuous wave forms (tone burst) and varies the signal frequency continuously between two limits (frequency sweeping). An oscilloscope screen displays the reflected signal amplitude (vertical axis) versus the frequency (horizontal axis). If a Lamb wave mode is generated for a particular angle, energy leaks through the fluid-solid interface in the form of leaky Lamb waves [20]. Destructive interference of the leaky Lamb waves with the back-surface reflection produces a null zone that is discernible as a dip (local minimum) in the amplitude-frequency plot of the reflected signal as shown in Figure 1. The corresponding phase velocity can be obtained using the following equation: $C_{ph}=C_w/\sin\Theta$ where C_{ph}: phase velocity, C_w: longitudinal wave speed in water (1490 m/sec), and Θ: angle of incidence. The null zone position changes in presence of an internal defect. Hence, when a defect is encountered the receiver voltage amplitude is altered and the image of the defect is generated. The major problem with this arrangement is that the null zone position is very sensitive to the plate thickness. Hence, a few percent change in the plate thickness alters the receiver voltage amplitude significantly. To avoid this problem one needs to filter the L-scan generated data through a special filter, called MFq filter {14}. This signal processing helps to minimize the effect of the plate thickness variation on the null zone but retains the sensitivity to defects of interest. Additional problem in the null monitoring technique is that the technique is very sensitive to the relative position among the plate, the transmitter and the receiver. In this research these problems are avoided/reduced by placing the receiver beyond the null zone as well as the specularly reflected zone. Exact expressions are provided to numerically calculate the positions of the transmitter and the receiver relative to the plate. Thus only propagating leaky Lamb waves are received by the receiver; apparently, its amplitude is comparatively less sensitive to the plate thickness and more sensitive to the defects inside the plate. A similar work with a single transducer has been reported in the literature by Nagy et al [6].

PULSE ECHO FOURIER TECHNIQUE OF LEAKY LAMB WAVE GENERATION

Fourier analysis of received leaky Lamb wave signals can also be used in the construction of dispersion curves in solid plates. In this technique, Lamb waves are produced by pulsed ultrasound generated using two broad band transducers positioned in a pitch-catch orientation as shown in Figure 2. The relative distances among the plate and the two transducers are set to specific values as per geometric calculations based on beam diffraction as shown in Figure 3. The transducers are then suitably defocused to produce a characteristic leaky lamb wave signal similar to the one shown in Figure 4. In contrast to the conventional tone burst method, leaky lamb wave signals are monitored in the nonspecular region rather than in the 'null' zone of the specular region. The plate wave signals in the nonspecular region are subsequently Fourier transformed to obtain a magnitude versus frequency spectrum. Peaks present in the spectrum indicate the presence of a Lamb wave root as shown in Figure 4. The phase velocity of the Lamb wave mode is calculated using geometric considerations (Figure 3). The information obtained from the transformations and calculations can be used to construct a dispersion curve.

EXPERIMENTAL APPROACH

Conventional Swept Frequency Technique

Theoretical dispersion curves produced by Kundu et al., [20] was used as the basis for these experiments. Experimental dispersion curves were constructed for a 1.6 mm thick stainless steel plate using the conventional method. One set of broad band transducers was used to generate the curves. The transducer used for the experiments were Aerotech Alpha 0.75" dia transducers of 3.5 MHz center frequency. The frequency sweeping was carried

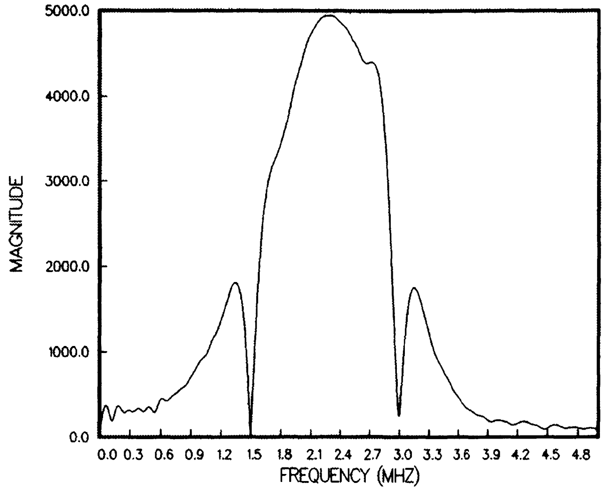


Figure 1 Spectral nulls produced in the conventional swept frequency 'null zone monitoring' method.

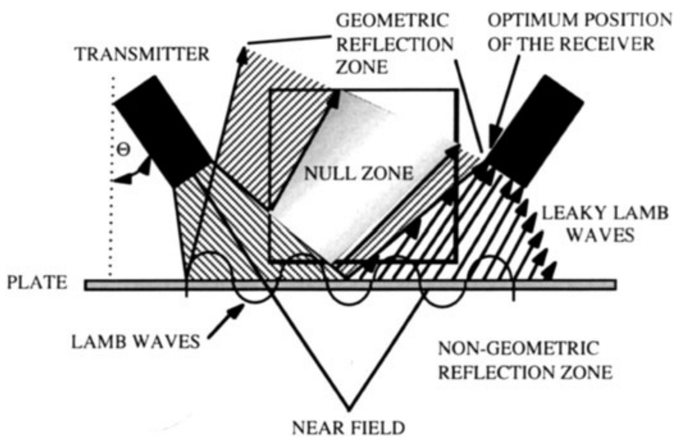


Figure 2 Schematic of the Optimum Geometry for the Fourier Analysis Technique.

out using a Wavetek 178 programmable wave form synthesizer in the interval from 1 MHz to 5 MHz. A Matec broad band receiver (Model 625), a Matec broad band gated amplifier (Model 310), and a Model 162 Boxcar averager were also used during the experiment. The incident angle of the waves was changed from 10 to 22 degrees at an interval of one degree.

Pulse Echo Fourier Analysis Technique

A dispersion curve was constructed for a 1.6 mm thick stainless steel plate using the Fourier analysis method. Two sets of broad band transducers were used to generate the curves. Information about these transducers is listed below:

Manufacturer:	Aerotech Alpha	PANAMETRICS V306
Frequency:	3.5 MHz	2.25 MHz
Diameter:	0.75 in	0.5 in.

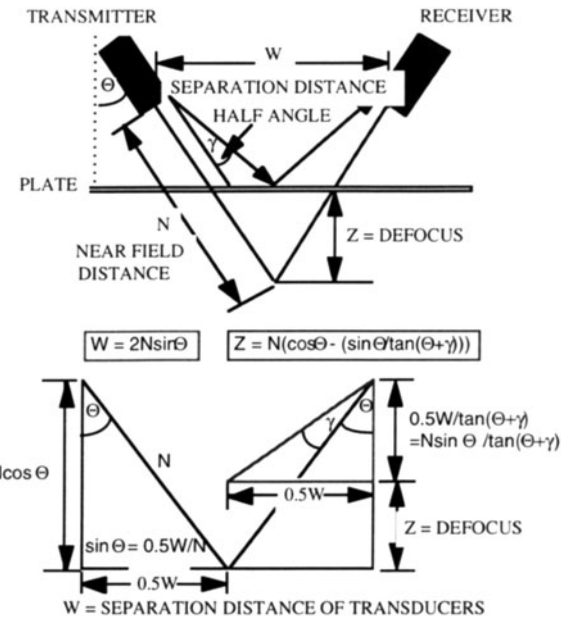


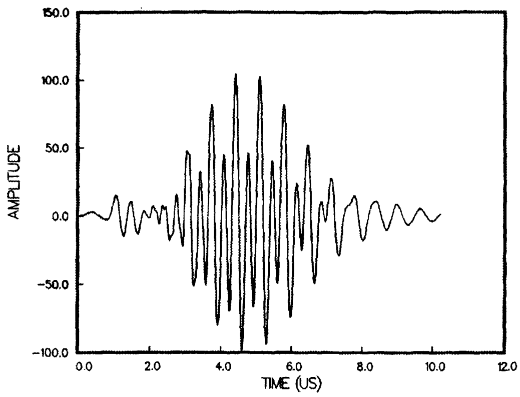
Figure 3 Geometric Considerations Based on Beam Diffraction and Nearfield Calculations

Equations used in the experimental setup for each pair of transducers are: $\lambda = c/f$, $N = (D^2-\lambda^2)/4l$, $\gamma_0 = \sin^{-1}(1.2*\lambda/D)$, where λ = Wavelength, c = Longitudinal velocity of sound in water (1490 m/sec), f = Frequency of transducer, N = Near-field distance, D = Diameter of transducer, and γ_0 = Half angle of transducer. These equations were used to calculate the wavelength, near-field distance, and half-angle of the transducers used in this study as shown in Table 1.

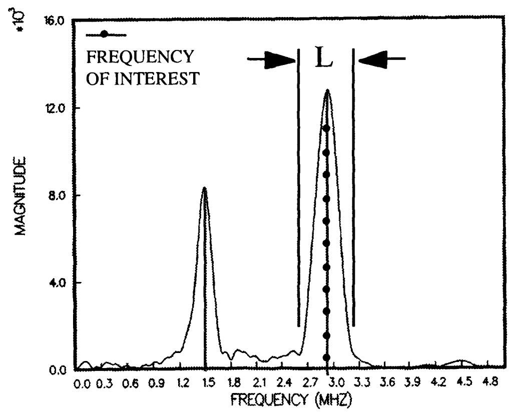
The 'range of validity' for positioning the receiver is illustrated in Figure 5. Any position in this region is suitable; however, a need exists to minimize attenuation due to leakage and to avoid the ambiguities that might be caused by inadvertent entry into the 'geometric reflection zone'. Therefore, the receiver needs to be as close to the transmitter as possible without entering the 'geometric reflection zone'. If the receiver is improperly positioned so that the edge of the receiver is slightly encroaching on the 'geometric reflection zone', ambiguity results as illustrated in Figure 6. Once the transducers were normalized and set to the proper angles, the tips of the transducers were separated by a distance W calculated by $W = 2*N*\sin\Theta$ (Figure 3). The approximate value of the defocus, z, was calculated using geometric considerations as shown in the following equation: $z = N*(\cos\Theta - (\sin\Theta/\tan(\Theta+\gamma)))$. Since the near field distance and half angle remain constant for a given transducer, z is only dependent on Θ. Minor changes were made in z during the experimental setup to obtain the characteristic lamb wave signal. The plate wave signals in the nonspecular region are subsequently Fourier transformed to obtain a magnitude versus frequency spectrum. Peaks present in the spectrum indicated

Table 1 Transducer Specifications and the corresponding near fields and half angles.

TRANSDUCER FREQUENCY	WAVELENGTH (in)	NEAR-FIELD DISTANCE (in)	HALF-ANGLE
2.25 MHz	0.0259	2.41	3.56
3.5 MHz	0.0167	8.43	1.53



(a)



(b)

Figure 4 (a) Received Signal when the Transducers are Properly Positioned as per the Calculations Shown in Figure 3. (b) Fourier Analysis of the Reflected (leaky) Signal in the Optimum Position

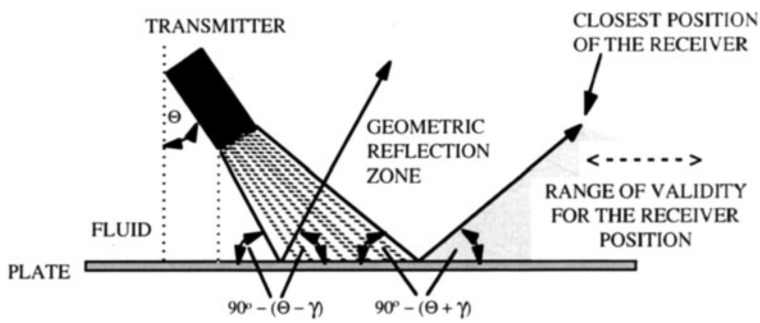
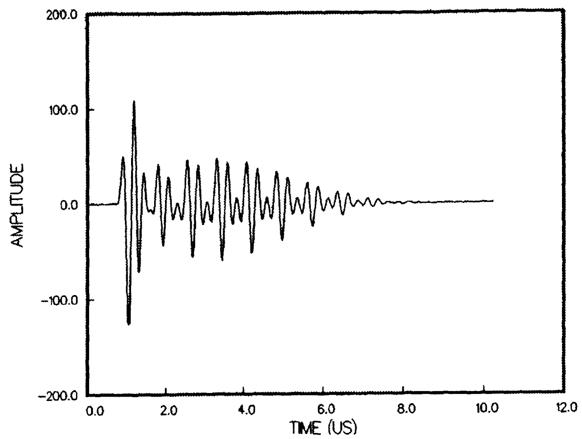
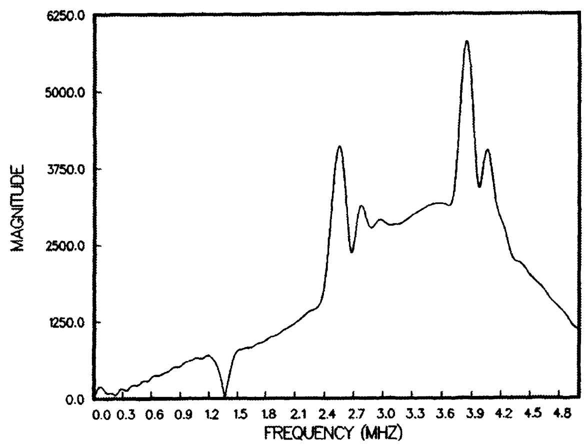


Figure 5 Valid Range of the Position of the Receiver for the Pulse Echo Fourier Technique.

thepresence of a Lamb wave root. The phase velocity of the Lamb wave mode was then calculated using the following equation: $C_{ph}=C_W/\sin\Theta$, where C_{ph}: phase velocity, C_W: longitudinal wave speed in water (1490 m/sec), and Θ: angle of incidence. The information obtained from the transformations and calculations was used to construct a dispersion curve.



(a)



(b)

Figure 6 (a) Received Signal when the Transducers are in an Undesirable Location Bounded by both the Geometric and Non-geometric Reflection Zones (b) Fourier Analysis of the Reflected (combination of specular and leaky) Signal Shown in Figure 6a.

RESULTS AND DISCUSSION

The dispersion curves generated using the conventional swept frequency and pulse-echo Fourier analysis techniques are shown in Figure 7. These experimental curves agree quite well with the theoretical dispersion curves generated by Tribikram Kundu. Any Lamb wave roots below 1 MHz were undetectable due to the limitations of the experimental equipment.

The pulse-echo Fourier analysis technique requires no frequency sweeping; therefore, additional equipment such as programmable waveform synthesizers, gated amplifiers, and boxcar averagers are not required, unlike the conventional method. In addition, slight changes in the vertical position of the transducers in the Fourier analysis technique does not affect the position of the peak as long as the transducer angle and experimental geometries are properly calculated. On the other hand, the minima in the reflected spectra of the conventional method are sensitive to the relative positions of the transducers and reflecting surface. Assuming a constant incident angle, slight changes in the vertical position of the transducers can cause the minima to shift on the frequency axis.

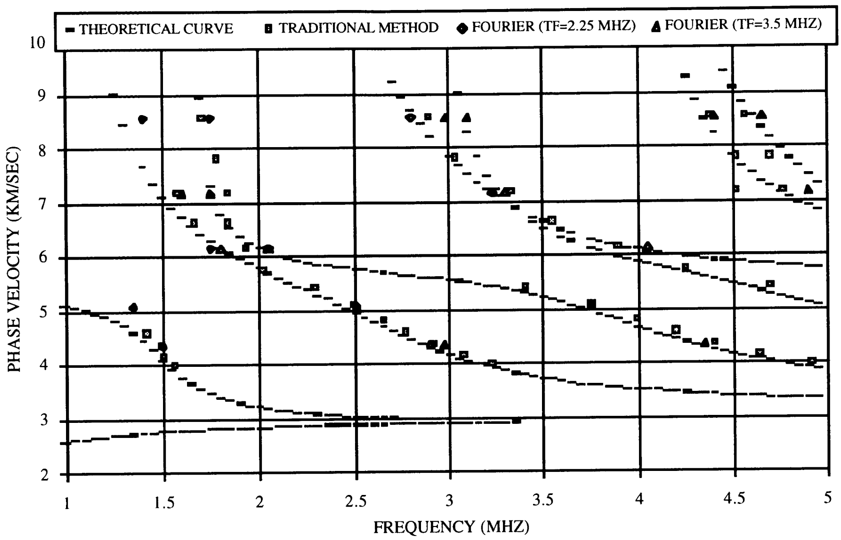


Figure 7 Theoretical Dispersion Curves Superimposed by Experimental Data Generated by the Two Methods (Traditional Swept Frequency and the Newly Proposed Pulsed Fourier Technique).

SUMMARY AND CONCLUSIONS

A novel method for constructing dispersion curves in solid plates using Fourier analysis of received leaky Lamb wave signals was developed and tested. In addition, Lamb wave dispersion curves were experimentally constructed using a conventional tone burst frequency swept technique. The experimental curves agreed quite well with the theoretical dispersion curves generated by Kundu [20]. A new method for constructing dispersion curves in solid plates using Fourier analysis of received leaky Lamb wave signals has been successfully verified by constructing a dispersion curve for a stainless steel plate. An advantage of this technique is its simplicity. No special type of transducer is required. In addition, the arrangement of the experimental components is based on simple geometric calculations and beam diffraction. The data repeatability and accuracy makes this method easy to standardize for practical applications such as the identification and classification of defects and material properties.

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